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QCD at the Tevatron: Status and Prospects

JOHN WOMERSLEY*

*Fermi National Accelerator Laboratory
Batavia, IL 60510 USA*

I shall review the present status of Tevatron QCD studies, focusing on the production of jets, vector bosons, photons and heavy quarks. In general there is good agreement between the results of current calculational tools and the experimental data. The major areas of discrepancy arise when the input parton distributions become uncertain (for example, jets at high E_T) or when the momentum scales become relatively small (for example, b production at low p_T). We can look forward to continued improvement in both calculations and measurements over the next decade. However, fully exploiting the power of the data will require considerable work, both from the experimentalists who must understand and publish all the systematic errors and their correlations, and from the phenomenologists who must understand the level of uncertainty in their calculations and in the parton distributions.

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*womersley@fnal.gov

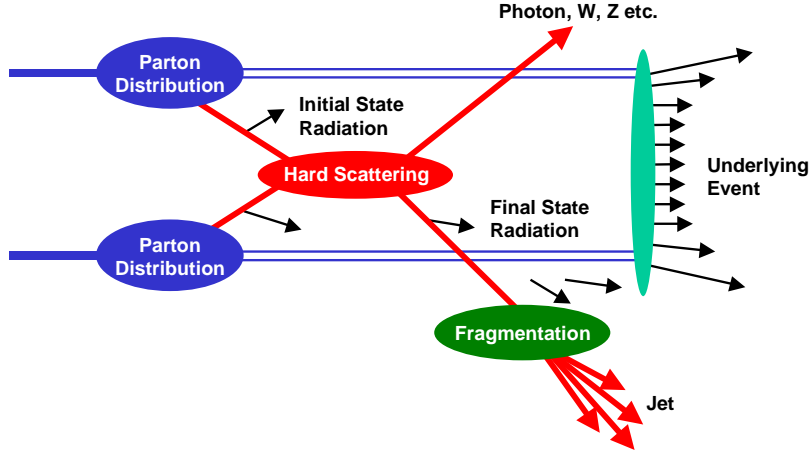


Figure 1: Schematic view of a hadron-hadron collision.

1 Introduction

It is over four years since data taking was completed in Run 1 at the Tevatron, so there are rather few new results to report. Instead, this presentation will be more of a review of the current state of knowledge, highlighting unresolved issues and prospects for Run 2. I shall briefly cover the production of jets, vector bosons, photons and heavy flavor. The opinions expressed are my own, and do not necessarily reflect the “party line” of the experiments.

The Tevatron collider recorded about 100 pb^{-1} of data during 1992–95 (Run 1), with two large detectors, CDF and DO. The results I shall show all come from this dataset, which was taken at $\sqrt{s} = 1.8 \text{ TeV}$ (with a small amount of running at 630 GeV). The detectors are now nearing the completion of major upgrades, and data taking will resume in March 2001 (Run 2). The goal is to accumulate 2 fb^{-1} by 2003 and 15 fb^{-1} by 2007. In Run 2, the machine will operate at $\sqrt{s} = 1.96 \text{ TeV}$.

In hadron-hadron collisions, the simple picture of perturbative hard scattering between point-like particles, as described for e^+e^- collisions by earlier speakers at this meeting, becomes complicated by the additional effects shown in Fig. 1:

- parton distributions — a hadron collider is really a broad-band quark and gluon collider;
- fragmentation of final state quarks and gluons;
- both the initial and final states can be colored and can radiate gluons, which may interfere;
- the presence of an underlying event from proton remnants.

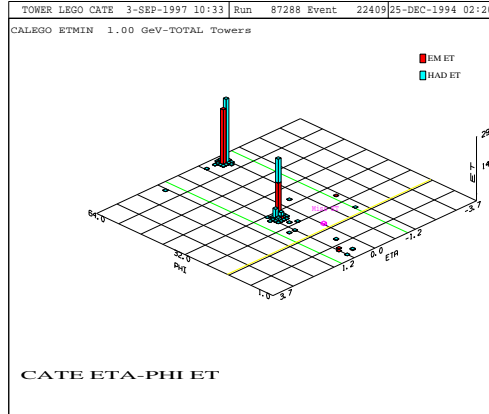


Figure 2: Lego plot of a high- E_T dijet event in DO. Towers with $E_T < 1$ GeV are suppressed.

Despite these potential complications, at sufficiently high energies the events appear quite simple: clear two-jet structure becomes obvious, as seen in Fig. 2, for example. Let us start by reviewing the status of jet production.

2 Jet Production

2.1 Inclusive Jet Cross sections at $\sqrt{s} = 1.8$ TeV

CDF[1] and DO[2] have both measured the cross section for $R = 0.7$ cone jets in the central rapidity region. The cross section falls by seven orders of magnitude between $E_T = 50$ and 450 GeV and both experiments' data are in pretty good agreement with NLO QCD over the whole range, as seen in Fig. 3. Looked at on a linear scale and normalized to the prediction, however, we have the situation shown in Fig. 4 (note that the CDF figure does not include systematic errors). The impression one gets is that there is a marked excess above QCD in the CDF data, which is not observed at DO. So much has been said about this discrepancy that it is difficult to know what can usefully be added¹ but I shall attempt to describe where we now stand.

In order to compare with CDF, DO carried out an analysis in exactly the same rapidity interval ($0.1 < |\eta| < 0.7$). The results[4] are shown in Fig.5. Firstly we note that there is no actual discrepancy between the datasets. Secondly, for this plot the theoretical prediction was made using the CTEQ4HJ parton distribution, which has been adjusted to give an increased gluon density at large x while not violating any

¹see Fig. 1 in [3].

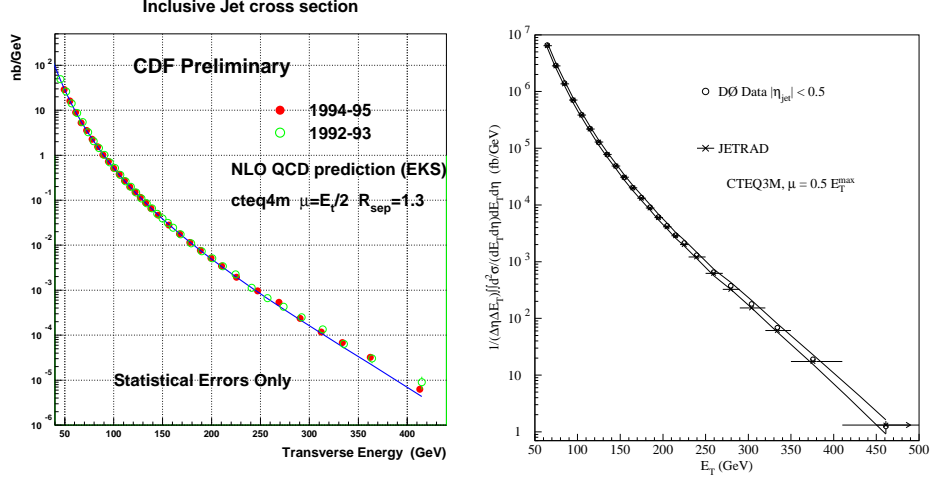


Figure 3: Inclusive jet cross sections measured at the Tevatron by CDF[1] (left, for $0.1 < |\eta| < 0.7$) and DO[2] (right, for $|\eta| < 0.5$), compared to the NLO QCD prediction.

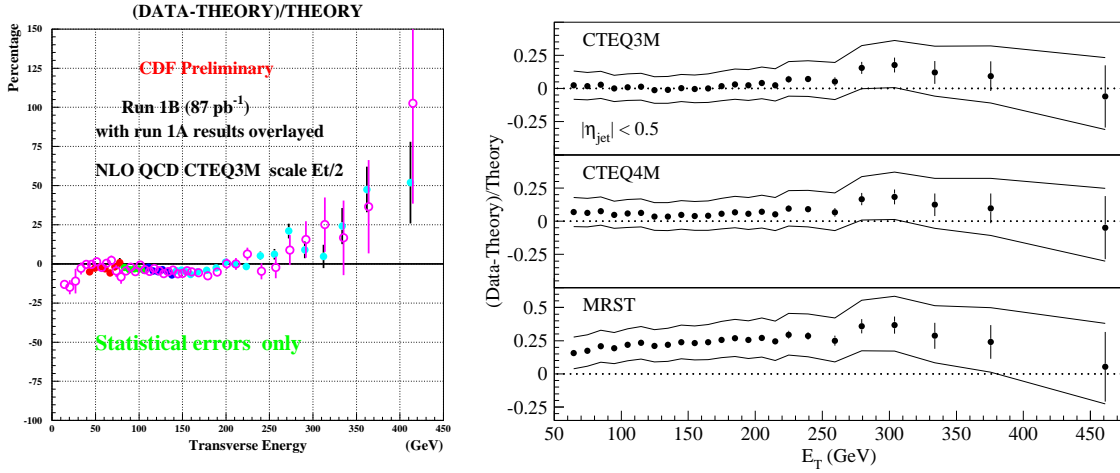


Figure 4: Inclusive jet cross sections measured at the Tevatron by CDF[1] (left, for $0.1 < |\eta| < 0.7$) and DO[2] (right, for $|\eta| < 0.5$), all normalized to the NLO QCD prediction.

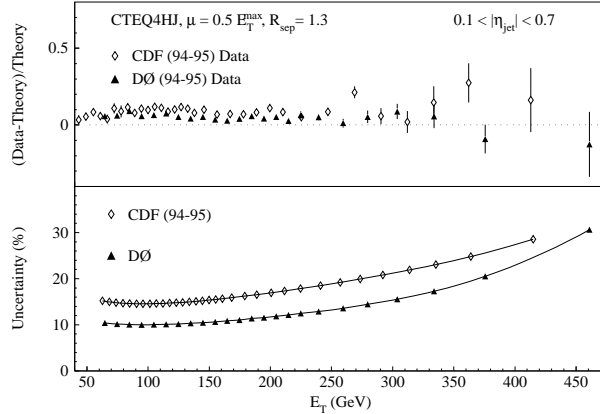


Figure 5: Inclusive jet cross sections for $0.1 < |\eta| < 0.7$ from CDF and DO, compared with CTEQ4HJ distribution; and size of the systematic errors on the two measurements. Taken from [4].

experimental constraints (except perhaps fixed target photon production data, which in any case require big corrections before they can be compared to QCD, as we shall see later). The result of this increased gluon content is improved agreement especially with the CDF data points. The situation with the latest CTEQ5M and CTEQ5HJ parton distributions is shown in Fig. 6, and again, the enhanced gluon content in CTEQ5HJ brings the predicted cross section closer to the CDF data.

What then have we learned from this issue? In my opinion, whether the CDF data show a real excess above QCD, or just a “visual excess,” depends critically on understanding the systematic errors and their correlations as a function of E_T . Whether nature has actually exploited the freedom to enhance gluon distributions at large x will only be clear with the addition of more data — the factor of 20 increase in luminosity in the first part of Run 2 will extend the reach by 70–100 GeV in E_T and should therefore make the asymptotic high- x behavior clearer. Whatever the Run 2 data show, this has been a useful lesson; it has reminded us all that parton distributions have uncertainties, whether made explicit or not, and that a full understanding of experimental systematics *and their correlations* is needed to understand whether experiments and theory agree or disagree.

DO[5] have extended their measurement of inclusive jet cross sections into the forward region. Figure 7 shows the measured cross sections up to $|\eta| = 3$. They are in good agreement with NLO QCD over the whole range of pseudorapidity and transverse energy; in fact both CTEQ4M and CTEQ4HJ parton distributions yield a good χ^2 .

Both Tevatron experiments have also studied dijet final states. CDF[6] has pre-

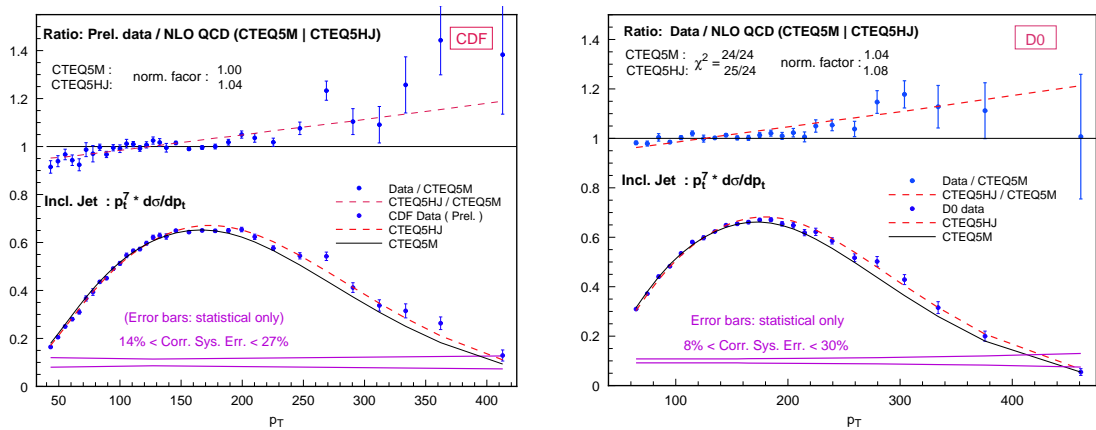


Figure 6: Inclusive jet cross sections measured by CDF (left) and DO (right), compared to the NLO QCD prediction using CTEQ5 parton distributions. The upper data points show $(data-theory)/theory$, while the lower points are the measured and predicted cross sections (approximately linearized though multiplication by E_T^7).

sented cross sections for processes with one central jet ($0.1 < |\eta_1| < 0.7$) and one jet allowed forward ($|\eta_2|$ up to 3.0). In Fig. 8 these are compared with the NLO QCD prediction as a function of the central jet's transverse energy (E_{T1}). The data show an excess above the theory for large E_{T1} , just as seen in the inclusive cross section; but since these events are common to both samples, this is not surprising.

DO have measured[5] the cross sections for dijet production with both same-side ($\eta_1 \approx \eta_2$) and opposite-side ($\eta_1 \approx -\eta_2$) topologies, for four bins of $|\eta|$ up to 2.0. The results are all in good agreement with the NLO QCD prediction.

All of these central, forward and dijet cross section measurements should really be used as input to the parton distribution fitting “industry”. Figure 9 shows where the Tevatron data lie on the plane of x and Q^2 , indicating their complementarity to the fixed target and HERA deep-inelastic data. The apex of the Tevatron phase space is set by the highest Q^2 event observed in Run 1, a spectacular dijet seen in DO with a jet-jet invariant mass of 1.2 TeV, $Q^2 = 2.2 \times 10^5 \text{ GeV}^2$, and $x_1 = x_2 = 0.66$.

2.2 Extraction of α_s

CDF have carried out an interesting study with the aim of extracting α_s from the inclusive jet cross section[7]; at NLO, the calculated cross section depends on α_s with a coefficient which is predicted by JETRAD. The result, $\alpha_s(m_Z) = 0.113^{+0.008}_{-0.009}$, is consistent with the world average, and α_s shows a nice evolution with scale (given by the jet transverse energy), as shown in Fig. 10. However the figure also shows that the measurement suffers from a large, and hard to quantify, sensitivity to the parton

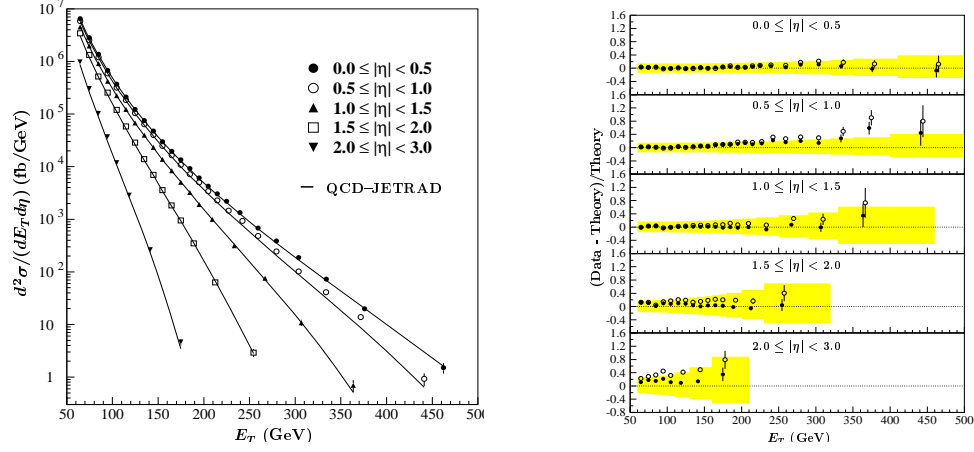


Figure 7: Inclusive jet cross sections measured up to $|\eta| = 3$ by DO[5], compared to the NLO QCD prediction (using the JETRAD Monte Carlo). In the left hand plot the prediction uses CTEQ4M; in the right hand plot the solid points use CTEQ4HJ while the open points use CTEQ4M.

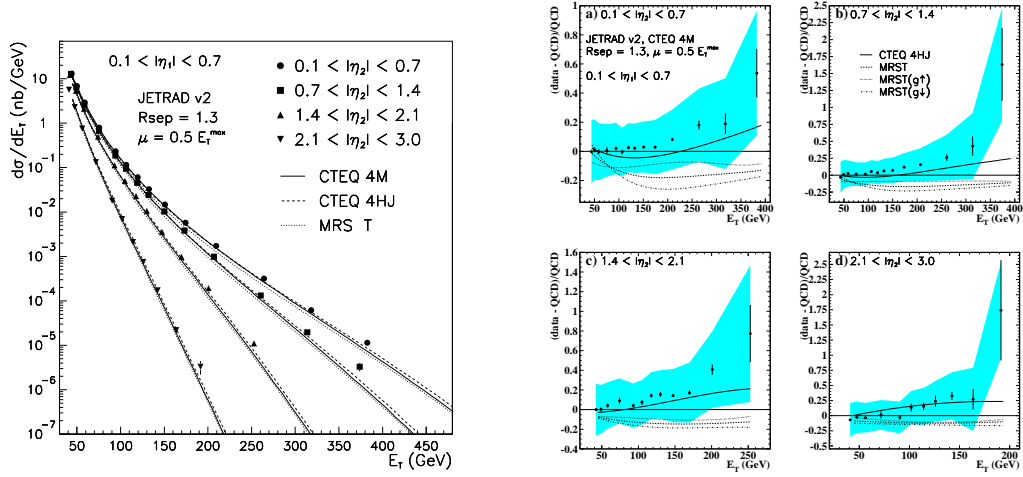


Figure 8: Dijet cross sections measured by CDF[6] for events with one central jet $0.1 < |\eta_1| < 0.7$ and one jet allowed forward; left, as a function of the central jet E_T for various bins of $|\eta_2|$, and right, normalized to the NLO QCD prediction (from JETRAD).

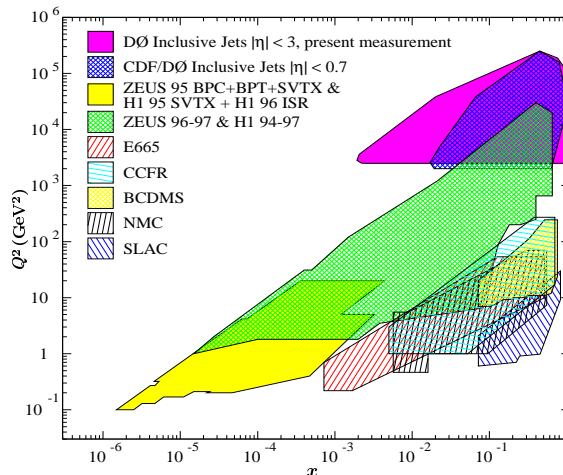


Figure 9: Phase space in x and Q^2 probed by various experiments, showing the potential of central and forward jet production at the Tevatron to constrain parton distributions in regions complementary to deep inelastic scattering. Taken from [5].

distributions, especially to the value of α_s assumed therein. At this time I think it must be characterized as a nice test of QCD and not really as a measurement of α_s .

2.3 Cross section ratio 630 GeV/1800 GeV

Both CDF[8] and DO[9] have exploited a short period of data taking at reduced center of mass energy towards the end of Run 1, to measure the ratio of scale invariant jet cross sections, $E_T^3 d^2\sigma/dE_T d\eta$ at $\sqrt{s} = 1800$ and 630 GeV. This ratio, as a function of scaled jet transverse energy $x_T = 2E_T/\sqrt{s}$, is shown in Fig.11. The ratio is expected to be a rather straightforward quantity to measure and to calculate — it would be exactly 1 in the pure parton model. Unfortunately the two experiments are not obviously consistent with each other (especially at low x_T) nor with NLO QCD (at any x_T). At least two explanations have been suggested for the discrepancy. Firstly, different renormalization scales could be used for the theoretical calculations at the two energies. While allowed, this seems unappealing.² An alternative explanation is offered by Mangano[10], who notes that a shift of a few GeV in energy between parton and particle level jets would bring the data in line with the prediction. Such

²Glover has suggested that such a procedure is in fact natural when a scaling variable like x_T is used; because x_T differs by a factor of about three between the two center of mass energies for a given E_T , a factor of three difference in the renormalization scales is appropriate.

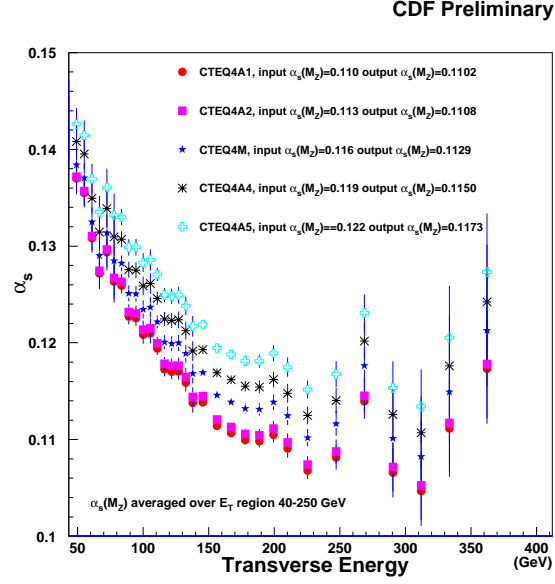


Figure 10: Value of α_s as a function of scale (jet transverse energy) inferred by CDF from the inclusive jet cross section using the CTEQ4A series of parton distributions[7].

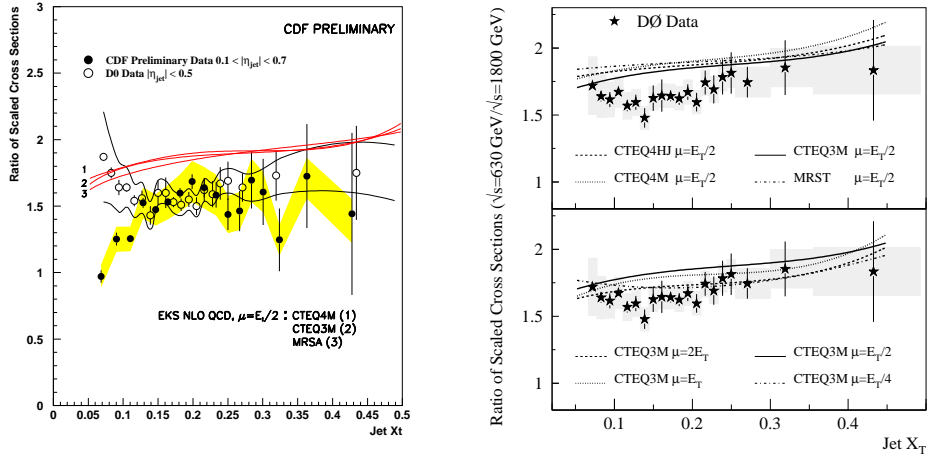


Figure 11: Scaled ratios of jet cross sections at $\sqrt{s} = 630 \text{ GeV}$ to $\sqrt{s} = 1800 \text{ GeV}$, as a function of $x_T = 2E_T/\sqrt{s}$, as measured by CDF[8] and DO[9] and as predicted by NLO QCD.

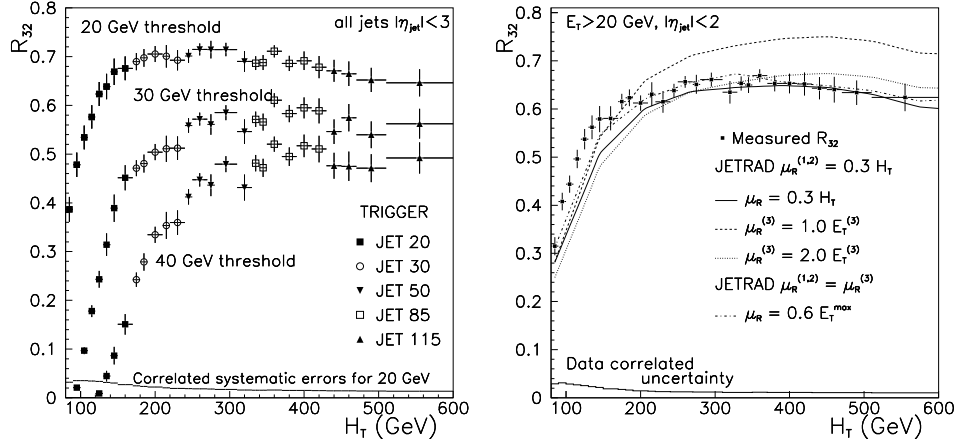


Figure 12: Ratio of events with three or more jets to those with two or more jets, R_{32} , measured as a function of $H_T = \Sigma E_T^{\text{jets}}$, for various jet thresholds (left) and compared with JETRAD (right).[11]

a shift might arise from non-perturbative effects such as losses outside the jet cone, underlying event energy, and intrinsic transverse momentum of the incoming partons; the shifts would likely be jet algorithm-dependent, and the two experiments might even obtain different results depending on how the jet energy scale corrections were done (based on data or Monte Carlo, for example). It seems that more work, both theoretical and experimental, is needed before this question can be resolved.

2.4 Ratio of 3-jet/2-jet Events

DO[11] have measured R_{32} , the ratio of events with ≥ 3 jets to those with ≥ 2 jets, as a function of $H_T = \Sigma E_T^{\text{jets}}$, for various third jet thresholds. This ratio (Fig. 12) is surprisingly large: two thirds of high- E_T jet events have a third jet with $E_T > 20$ GeV and about half have a third jet above 40 GeV. It is interesting to ask if this ratio can be predicted by QCD. The answer is yes, reasonably well, even by JETRAD (which of course is a leading order calculation of R_{32}). DO have also attempted to extract information on the optimal renormalization scale for the emission of the third jet: should it be the same scale as the leading jets, or should the third jet emission be treated as part of a parton shower with an “evolving” scale related to the third jet’s E_T ? (A specially modified version of JETRAD was used for this study). They find that a scale tied to the first two jets is better than one related to the third jet E_T . Whether this tells us much about nature or merely about JETRAD I don’t know, but it’s interesting given the widespread use of the parton shower approximation to generate additional jets in HERWIG and PYTHIA.

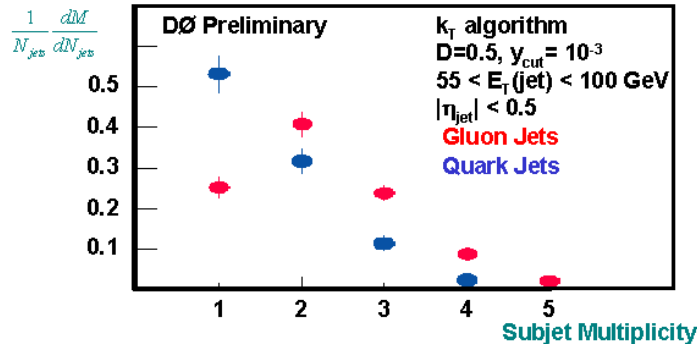


Figure 13: Subject multiplicities measured by DO using a k_T algorithm to find clusters within jets; distributions for quark and gluon jets are inferred using $\sqrt{s} = 1800$ GeV and $\sqrt{s} = 630$ GeV data[12].

2.5 Jet Structure and Quark/Gluon Separation

All the results presented so far have used a cone jet finder. By running a k_T jet finder inside previously identified jets, one can count the number of “subjets” or energy clusters. Doing this (rather than, for example, counting charged tracks) allows the *coarse* jet structure corresponding to the initial, perturbative part of fragmentation to be studied. DO[12] have made such a measurement and, by comparing jets of the same E_T and η recorded at $\sqrt{s} = 1800$ and 630 GeV, have inferred the composition of pure quark and gluon jets. The extracted subjet multiplicity M for the two species is shown in Fig.13. The ratio of $M - 1$ for the two cases, which might naively be expected to equal the ratio of gluon and quark colour charges, is found to be 1.91 ± 0.04 , compared with 1.86 ± 0.04 from HERWIG. This is very encouraging and might even suggest that we have glimpsed the holy grail of quark-gluon jet separation. The true test, however, remains the use of the subject multiplicity as a discriminant in an analysis like the search for $t\bar{t} \rightarrow 6$ jets. Such a test will probably have to wait for Run 2.

3 Weak Boson production

Next-to-next-to leading order (order $\alpha \cdot \alpha_s^2$) predictions exist for the W and Z production cross sections times decay branching ratios into leptons. The experimental values from CDF and DO (Fig. 14) are in excellent agreement with these predictions, both for electrons and muons. In fact, the careful reader will note that the CDF cross sections are a few percent higher than those from DO; this is consistent with the fact that CDF use a luminosity normalization which is 6.2% higher than DO’s (the two

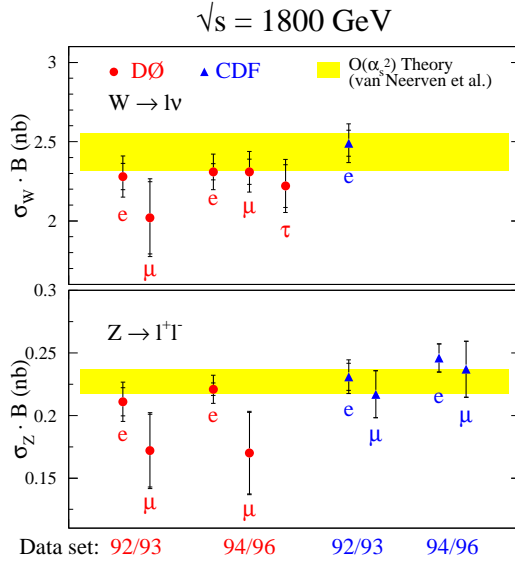


Figure 14: Vector boson production cross sections measured at the Tevatron by CDF and DO, compared to the NNLO QCD prediction.

experiments assume different total $p\bar{p}$ inelastic cross sections). It is therefore tempting to conclude that the W/Z cross sections are the better known quantity, and indeed it has been seriously proposed to use σ_W as the absolute luminosity normalization basis in Run 2. Walter Giele's contribution in these proceedings contains some more discussion of the systematics associated with such an approach.

3.1 Z Transverse Momentum

As well as increasing the total cross section, the QCD predictions change the transverse momentum distribution of the produced boson. The most straightforward measurement is for the Z since it can be directly reconstructed from two decay leptons. Figure 15 show recent DO results on the transverse momentum distribution of the Z boson[13] compared with a variety of QCD predictions. Clearly the fixed-order NLO QCD is not a good match for the data, while the resummed formalism of Ladinsky and Yuan[14] fits rather well. This approach uses fixed-order QCD at high p_T^Z matched to a resummation of the large logarithms of m_Z^2/p_T^2 at low p_T^Z . The resummed calculations always include some nonperturbative parameters that must be extracted from the data, and various authors have used different values for these. This probably accounts for the fact that the resummed calculations of Davies, Webber and Stirling[15], and of Ellis and Veseli[16] (also shown in the figure) do not offer quite as good a description of the data.

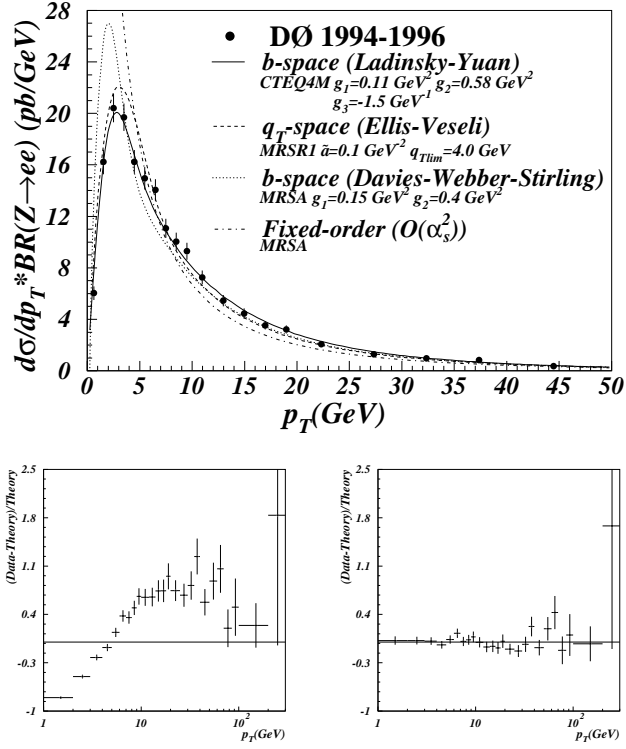


Figure 15: Transverse momentum distribution of the Z , as measured by DØ[13]. The upper plot shows the data and various calculations. The lower left shows the data normalized to the fixed-order QCD prediction and the lower right shows the data normalized to the resummed calculation of Ladinsky and Yuan[14].

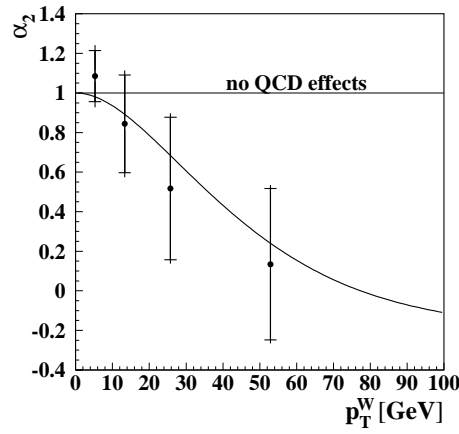


Figure 16: Extracted value [17] of α_2 (the coefficient of $\cos^2 \theta^*$ in the angular distribution of electrons from W decay) as a function of p_T^W . The measurement is in good agreement with QCD.

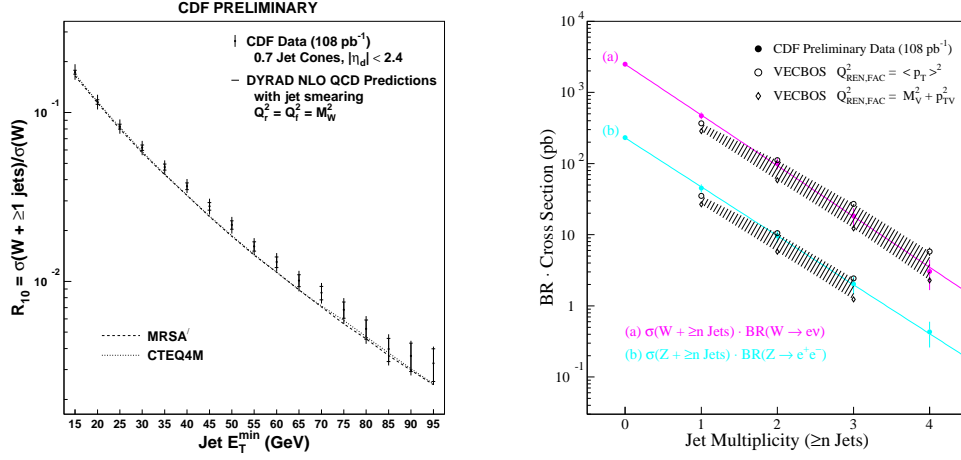


Figure 17: The left hand plot shows the ratio of the $W +$ (one or more) jets cross section to the inclusive W cross section at the Tevatron, as measured by CDF[18]. The right hand plot shows the $W + n$ jets and $Z + n$ jets cross sections as a function of the number of jets n .

DO have also observed[17] the effect of QCD corrections in the angular distribution of electrons from W decay. Figure 16 shows the extracted value of α_2 (the coefficient of $\cos^2 \theta^*$ in the angular distribution) as a function of p_T^W . The measurement is in good agreement with QCD.

3.2 $W + \text{jets}$

QCD also predicts the number and spectrum of jets produced together with the vector boson. DO used to show a cross section ratio $(W + 1\text{jet})/(W + 0\text{jet})$ which was badly in disagreement with QCD. This is no longer shown: the data were basically correct, but there was a bug in the way DO extracted the ratio from the DYRAD theory calculation.

Recent CDF measurements of the $W + \text{jets}$ cross sections[18] agree well with QCD, as shown in Fig. 17. The figure shows the fraction of W 's with 1 or more jets, compared with the NLO prediction; and the $W + n$ jets rate, compared with the LO prediction (for a variety of renormalization scales). Alas, it seems that there is little prospect for being able to extract α_s from these measurements, as had been hoped. This is because the $W + \text{jet}$ cross section depends on α_s both in the jet production vertex and in the parton distributions, and these two factors largely cancel in the kinematic range probed at the Tevatron.

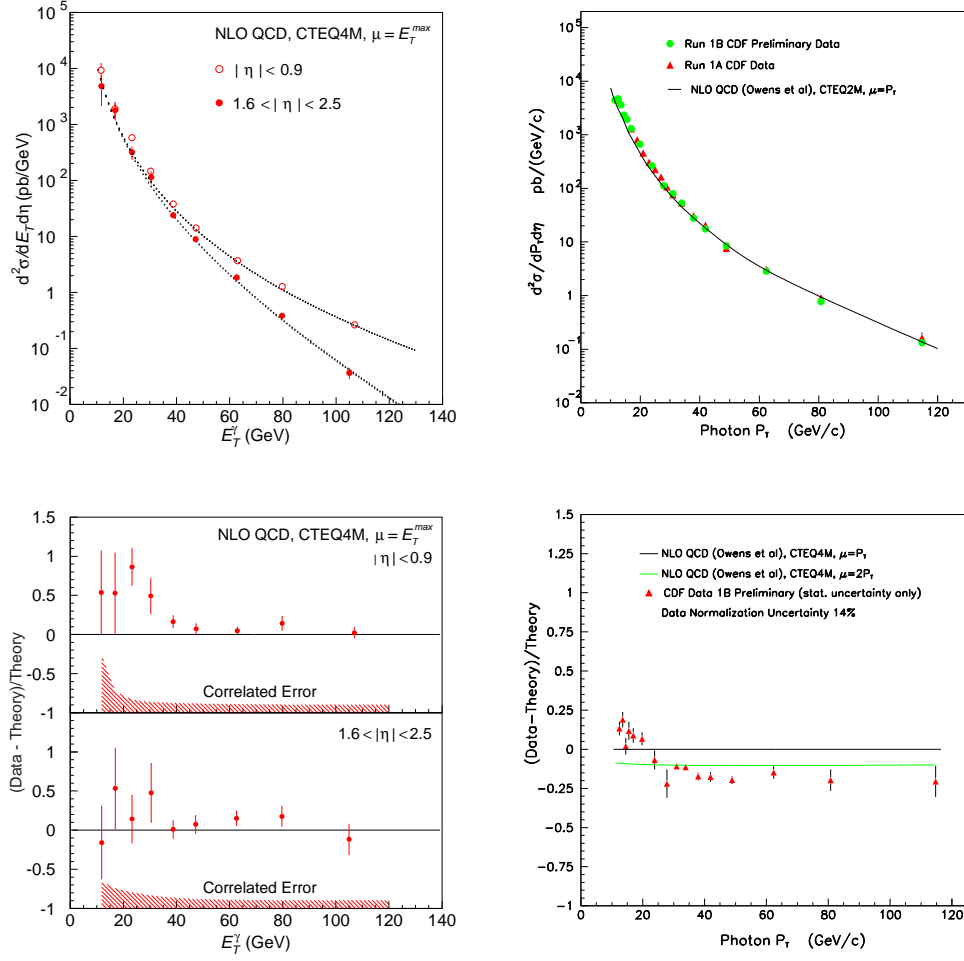


Figure 18: Inclusive isolated direct photon cross sections at the Tevatron; the left hand plots show DO[19] measurements and the right hand plots show the latest CDF results[20] (statistical errors only). All are compared with the NLO QCD prediction of Owens *et al.*[21].

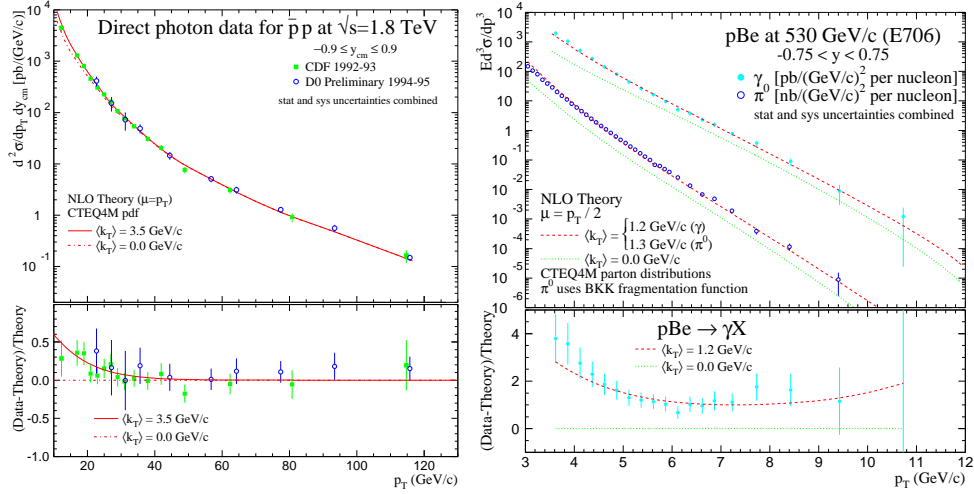


Figure 19: The isolated photon cross section at the Tevatron (left hand plots) showing the improved agreement with QCD if 3.5 GeV of transverse momentum smearing (“ k_T ”) is added to account for soft gluon emission. The right hand plot shows the isolated photon and π^0 cross sections measured by E706[23], compared with the NLO QCD prediction with and without 1.2 GeV of additional k_T smearing.

4 Isolated Photon Production

Historically, many authors hoped that measurements of direct (or prompt) photons would provide a clean test of QCD, free from the systematic errors associated with jets, and would help pin down parton distributions. In fact photons have not lived up to this promise — instead they revealed that there may be unaccounted-for effects in QCD cross sections at low E_T . (Because photons can typically be measured at lower energies than jets, they provide a way of exploring the low- E_T regime). Results from the Tevatron experiments [19][20] are shown in Fig. 18. While the general agreement with the NLO calculation of Owens and collaborators[21] is good, there is a definite tendency for the data to rise above the theory at low transverse energies.

An often-invoked explanation for this effect is that there exists additional transverse momentum smearing of the partonic system due to soft gluon radiation. The magnitude of the smearing, or “ k_T ”, is typically a few GeV (at the Tevatron), motivated in part by the experimentally measured p_T of the $\gamma\gamma$ system in diphoton production which peaks around 3 GeV[22]. PYTHIA simulations of photon production also suggest that the most probable transverse momentum of radiated initial state gluons is 2–3 GeV[20]. Inclusion of such k_T through Gaussian smearing in the calculation gives much better agreement with the data, as shown in Fig. 19. Much larger deviations from QCD are observed in fixed-target experiments such as E706 at Fermilab[23]. Again, Gaussian smearing (with $k_T \approx 1.2$ GeV in this case) can

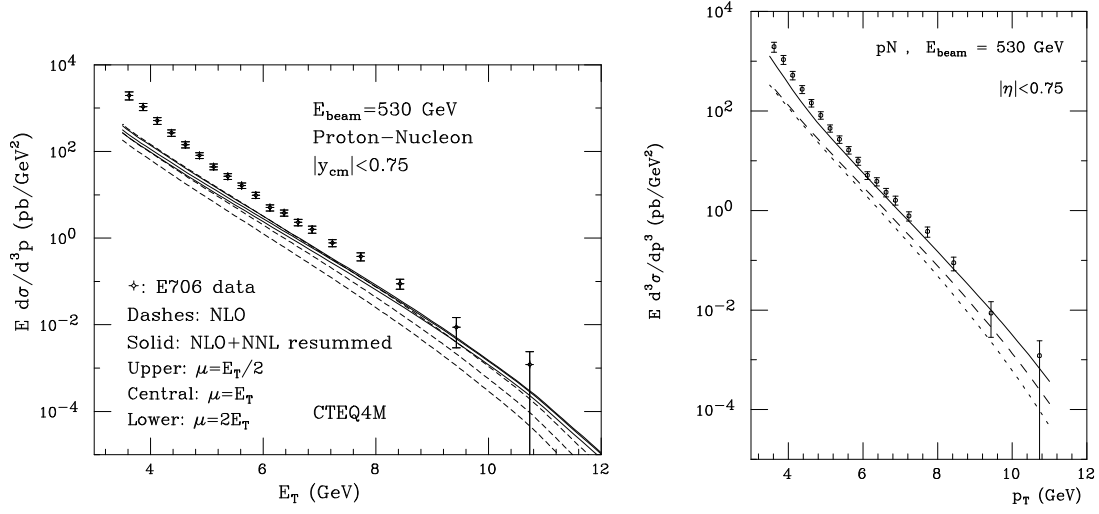


Figure 20: Resummed calculations of isolated photon production compared with the E706 data; left, by Catani *et al.*[25] and right, by Laenen, Sterman and Vogelsang[27].

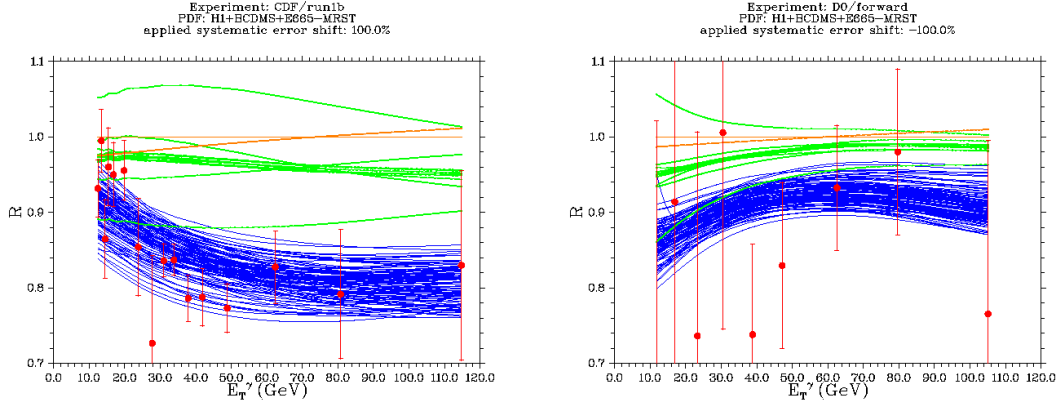


Figure 21: Isolated photon cross sections measured in the central region by CDF (left) and the forward region by DO (right), compared with NLO QCD predictions. The blue curves use an ensemble of PDF's proposed by Giele, Keller and Kosower, derived by fitting to H1, BCDMS and E665 data. The range of predictions gives a measure of the uncertainty on the PDF. The green curves use MRS99 distributions and the orange curves are CTEQ5M and 5L. No additional k_T smearing is included.

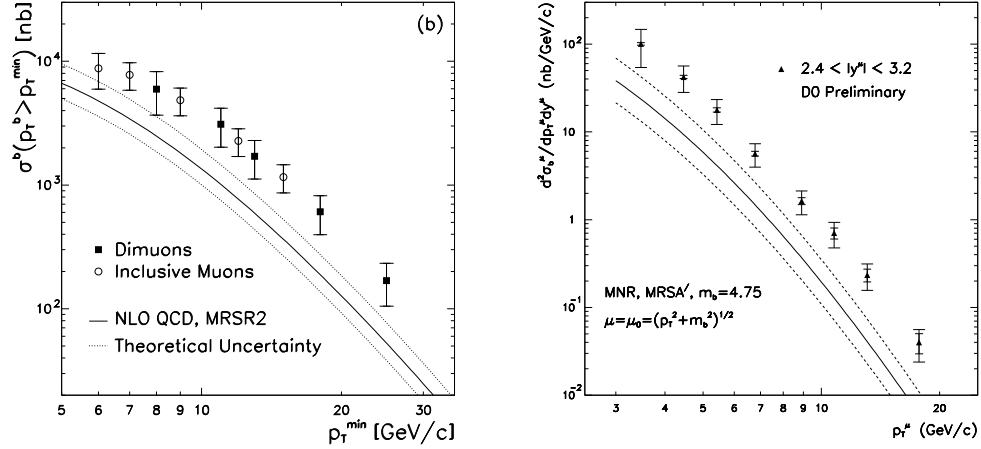


Figure 22: Cross sections for b production at the Tevatron compared with NLO QCD predictions, as measured by DO[29]; left, central rapidity region, and right, forward.

account for the data, as also shown in the figure.

Unfortunately the predictive power of Gaussian smearing is small: it cannot really tell us what happens to forward photons, or what happens at the LHC, for example. The “right way” to treat soft gluon emission should be through a resummation calculation which works nicely for $\gamma\gamma$ and W/Z transverse momentum distributions. Initial attempts did not seem to model the E706 data[25][26], but more recent calculations include additional terms and look more promising[27] (Fig. 20).

A rather different view is expressed by Aurenche and collaborators[24], who find their calculations, *sans* k_T , to be consistent with all the ISR and fixed-target data with the sole exception of E706. They say, “it does not appear very instructive to hide this problem by introducing an arbitrary parameter fitted to the data at each energy,” by which they mean k_T .

The latest result in this saga is most interesting. Elsewhere in these proceedings, Walter Giele reports that he is able to obtain good agreement (Fig. 21) between the Tevatron data and QCD, without any k_T , with a newly derived set of PDF’s that are extracted from DIS data from H1, BCDMS and E665. If correct, this observation could render the whole discussion moot — there would be no discrepancy with QCD here at all, merely another indication that we need to understand parton distribution uncertainties!

In summary, direct photon production has proved extremely interesting and remains quite controversial. The appropriateness of a Gaussian k_T treatment is still hotly debated, the experiments may not all be consistent, and the latest results merely increase the mystery — is it all just the PDF’s?

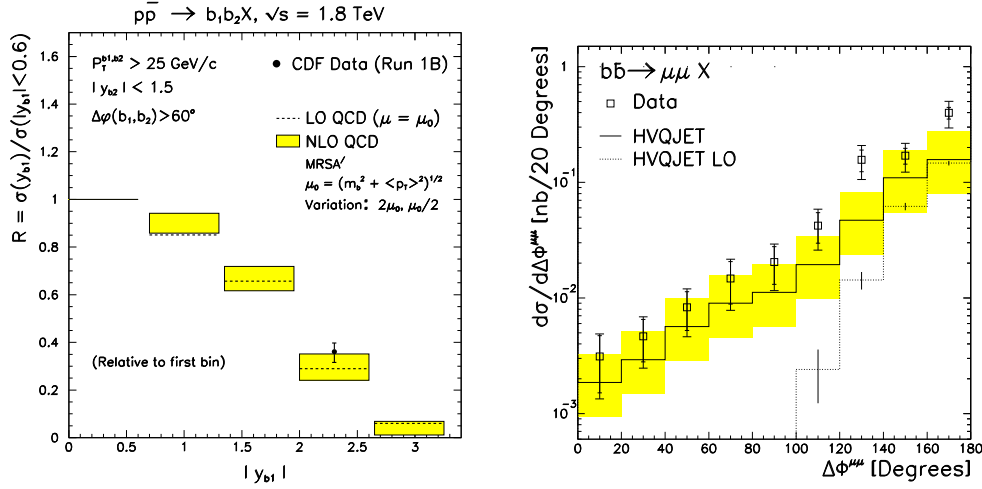


Figure 23: Correlations between b -jets at the Tevatron compared with NLO QCD predictions; (left) rapidity correlations as measured by CDF (normalized to the first bin), and (right) azimuthal angle correlations as measured by DO.

5 Heavy Flavour Production

At the Tevatron, the measured inclusive b -quark and B -meson production cross sections continue to lie a factor of about two above the NLO QCD expectation. This is seen by both CDF[28] and DO[29] in the central and forward regions (the difference is perhaps even larger for forward b production, as seen in Fig. 22). On the other hand, NLO QCD does a good job of predicting the shape of inclusive distributions, and of the correlations between b quark pairs (Fig. 23), so it seems unlikely that any exotic new production mechanism is responsible for the higher than expected cross section. In passing, it is interesting to note that a similar excess is also seen in b -production at HERA[32][33] and in $\gamma\gamma$ collisions at LEP2[31].

Recently, DO have extended these measurements to higher transverse momenta (up to 100 GeV)[30]. The results (Fig.24) are interesting: the measured cross section comes closer to the prediction around $p_T \sim 50$ GeV and above. It is therefore tempting to compare the shape of $(Data - Theory)/Theory$ for b -jets and for photons, as I have done in Fig. 25. The plot compares DO photons, CDF photons (renormalized by 1.33) and DO b -jets (compared with the highest of the range of QCD predictions). The plot is perhaps quite suggestive that the same explanation may be relevant for photons and b -jets — whatever that may be!

If the heavy flavour is heavy enough, QCD seems to work rather better. The current state of measured and predicted top cross sections is summarised in Table 1. This includes the latest (revised) CDF measurement. There is an excellent agreement

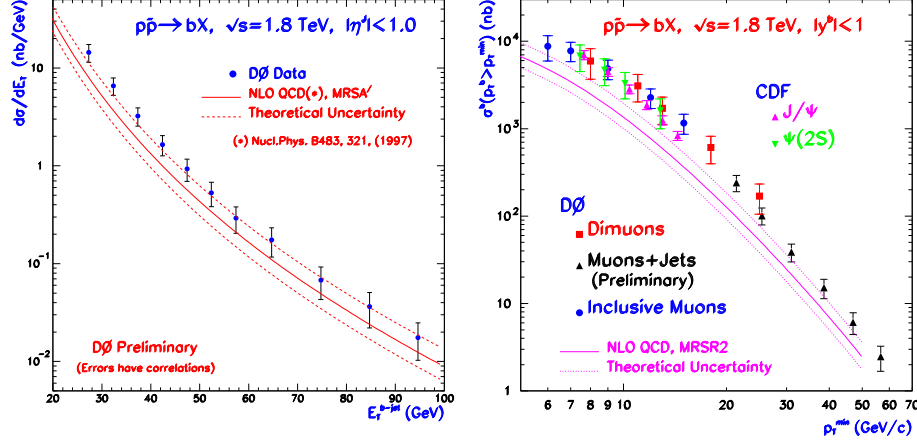


Figure 24: New measurements of high- p_T b -jet production at the Tevatron compared with NLO QCD predictions, as measured by DO[30]; (left) differential cross section as a function of E_T^{jet} ; (right) integral cross section as a function of p_T^b .

| Authors | Cross Section (pb) |
|-----------------------------|--|
| CDF[34] | $6.5^{+1.7}_{-1.4}$ (at $m_t = 175$ GeV) |
| DO[35] | 5.9 ± 1.7 (at $m_t = 172$ GeV) |
| Bonciani <i>et al.</i> [36] | 5.0 ± 1.6 |
| Berger and Contopanagos[37] | $5.6^{+0.1}_{-0.4}$ |
| Kidonakis[38] | 6.3 |

Table 1: Top production cross sections at the Tevatron, measured and predicted.

between data and theory, though one may note that the most recent (resummation) calculation[38] lies outside the band of uncertainty claimed by earlier authors[37].

6 Prospects

What can we look forward to in Run 2 and beyond? Clearly there will be lots more data — the next decade belongs to the hadron colliders. We can also expect improved calculations (NNLO calculations, NLL resummations). There is a lot of work going on towards the goal of correctly treating uncertainties in PDF's, as manifested by Walter Giele's contribution to these proceedings. This is a great step forward, but it does impose significant work on the experiments, who must understand and publish all the errors and their correlations.

We can also look forward to improved jet algorithms. There is a CDF-DO accord

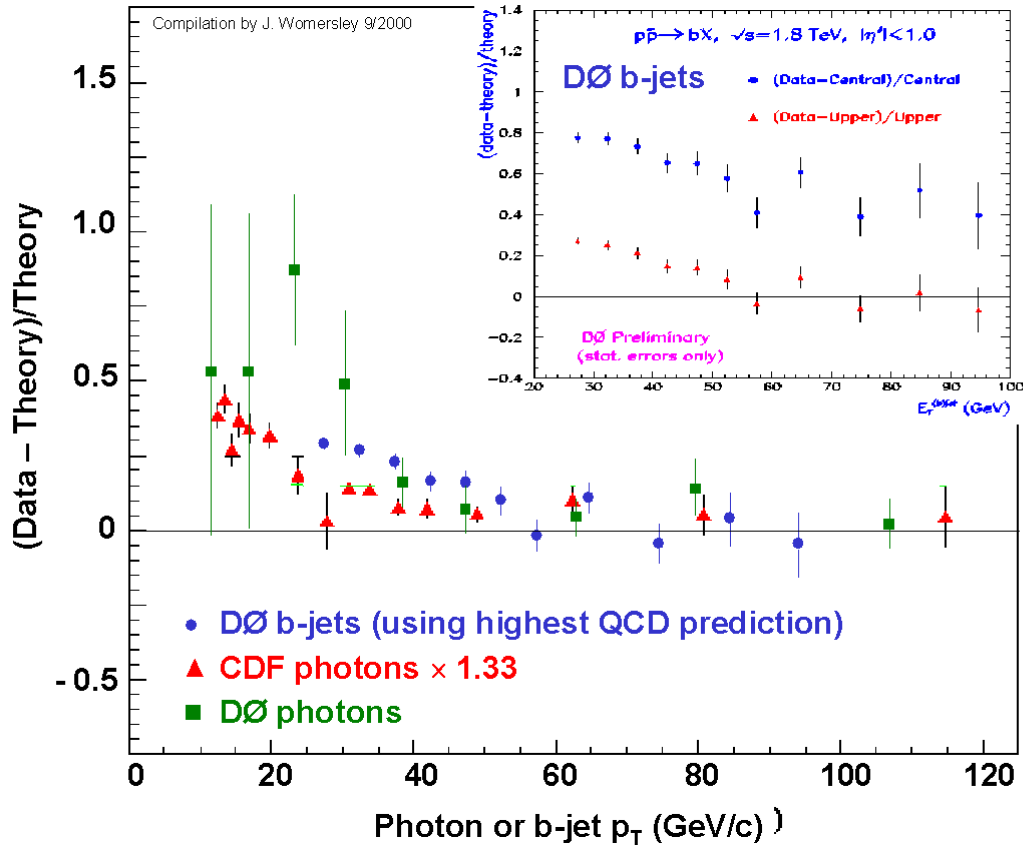


Figure 25: Compilation of b -jet and isolated photon cross sections compared with QCD.

from the Fermilab Run 2 QCD workshop. The k_T algorithm will be used from the start, and the experiments have agreed upon one common implementation. They will also try to make the cone algorithm theoretically more acceptable by modifying the choice of seeds (or even through a seedless version).

I would also like to see a theoretical and experimental effort to understand the underlying event, and include it in the predictions. The current approach is to subtract an “underlying event contribution” from the jet energies. This assumes factorization between the hard scattering and the underlying event, and while this is a reasonable approximation it is bound to break down at the GeV level because the hard event and the underlying event are color-connected. Indeed, HERWIG suggests that at the 1–2 GeV level jets pick up or lose energy to the rest of the event depending on the jet algorithm. This is another example of how greater precision demands greater care: approximations and assumptions that used to be “good enough” can no longer be taken for granted. In fact there are very nice new results from CDF on the under-

lying event[39]. Understanding the underlying event would also allow a consistent treatment of double parton scattering.

Finally, one may hope for a consistent approach to hard diffraction processes. High E_T jets and W production are hard processes which should be amenable to perturbative calculation, even if the final state is such that one of the nucleons does not break up. We need to break down the walls of the “pomeron ghetto” and stop trying to describe these processes in a language which, in my opinion, does not promote understanding.

7 Conclusions

Tevatron QCD measurements have become precision measurements. We are no longer testing QCD; we are testing our ability to make precise calculations within the framework of QCD. The state of the art is NNLO calculations, NLL resummations, and measurement errors at the 5% level. This level of precision demands considerable care both from the experimentalists and the phenomenologists, in understanding jet algorithms, jet calibrations, all the experimental errors and their correlations, and the level of uncertainty in the calculations and in the PDF's.

In general our calculational tools are working well. The open issues generally relate to attempts to push calculations closer to the few-GeV scale (b production at modest p_T , perhaps low- E_T photons) and/or to regions where the parton distributions are uncertain (high- E_T jets, and perhaps photons).

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